

Sputter optimization of AlN on diamond substrates for high frequency SAW resonators

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Abstract—The AlN/diamond structure is an attractive combination for SAW devices and its application at high frequencies. In this work, the synthesis of AlN thin films by reactive sputtering has been optimized on diamond substrates in order to process high frequency devices. Polished microcrystalline and as-grown nanocrystalline diamond substrates have been used to deposit AlN of different thickness under equal sputtering conditions. For the smoother substrates, the FWHM of the rocking curve of the (002) AlN peak varies from 3.8° to 2.7° with increasing power. SAW one port resonators have been fabricated on these films, whose electrical characterization (in terms of S11 parameters) is reported.

Keywords—AlN, sputtering, diamond, SAW, high-frequency.

I. INTRODUCTION

High-frequency surface acoustic wave (SAW) devices are needed more and more as the demand of large volume data transmission is required for mobile phones, satellite broadcasting and wireless network systems. The center frequency is determined by $f = V_p/\lambda$, where f is the center frequency, V_p the phase velocity of the SAW material and λ the wavelength [1]. In order to increase the frequency we can either decrease the wavelength, which depends on the size of the interdigital transducers (IDTs), or increase the phase velocity, which depends on the material. The first option entails the introduction of e-beam lithography on the manufacturing process. The alternative choice requires a careful selection of a piezoelectric layer and a substrate with a high V_p .

AlN/Diamond is a perfect combination for high-frequency SAW devices. Diamond has the highest SAW velocity among all solids, around 11000 m/s. AlN is a piezoelectric material when it is oriented on c -axis. It has also one of the highest sound velocities among all piezoelectric materials, 5600 m/s. Hence, the velocity dispersion in the AlN/Diamond system is small [1].

A critical aspect of the AlN layers deposited by reactive sputtering is their surface roughness, as it may lead to an increase of propagation losses. This roughness is related to the surface roughness of the substrate, in this case CVD (Chemical Vapor Deposition) synthesized diamond.

In this work, we study the influence of the diamond substrate roughness and the thickness of the AlN thin films deposited by reactive magnetron sputtering. The final goal is to optimize these AlN thin films in order to process SAW devices.

II. EXPERIMENTAL

Thin AlN films were deposited in a home built balanced magnetron sputter deposition system. It consists on two chambers (load lock chamber, and process chamber) evacuated by 800 l/s turbomolecular pumps. This configuration allows us to achieve $< 5 \cdot 10^{-8}$ mBar before each run. The process gases, argon and nitrogen, were introduced through 100 sccm (Ar) / 100 sccm (N₂) mass flow controllers. Both of them were N70 quality or better. The Al target (99.999% purity) was water-cooled on the backside. The target was powered by an ENI RPG50 asymmetric bipolar-pulsed DC generator. The applied frequency was 250 kHz while the duration of the positive pulse (13% of the total signal period) was 496 ns, with an amplitude of +40 V.

Nano and microcrystalline diamond, NCD and MCD, were used as a substrate, the MCD substrates have been polished after their CVD. Prior to each deposition, the substrates were carefully cleaned using a standard procedure, rinsing in pirrolidone for 5 min, acetone at 60°C for 5 min, and a propanol ultrasonic bath. The chamber was conditioned by a pre-sputtering process before each experiment including 7 min in pure Ar and 5 min in a reactive atmosphere. The parameters used for the conditioning and deposit are shown in table I. These parameters allowed us to obtain highly c -axis oriented AlN films on different substrates as described in previous works [2].

TABLE I. CONDITIONING AND SPUTTERING PARAMETERS.

	Pre-sputtering	Sputtering
Power [W]	500	400-700
Pressure [mTorr]	10	3
Gas Flow Ar/N ₂ [Sccm]	30/0	3/9
Substrate temperature [°C]	RT	RT
Target-Substrate Distance [mm]	45	45
Time [min]	7	15

$\theta/2\theta$ and rocking curve X-ray diffraction analysis were used to determine the crystallographic quality of the AlN thin film, by means of a Phillips X-Pert Pro MRD diffractometer. The surface roughness was measured using a Digital Instruments Nanoscope III atomic force microscope (AFM). Conventional transmission electron microscopy (CTEM) analysis in electron diffraction mode either using SAED (selective area diffraction pattern, reciprocal space) or micrographs in bright (BF) and dark field (DF) conditions, was performed for structural characterization on cross-sectional prepared samples using a Jeol 1200 EX electron microscope operating at 120 keV. TEM sample preparation was carried out by mechanical cutting, grinding and ion milling to get electron transparency.

III. RESULTS AND DISCUSSIONS

Synthesis of AlN on diamond is a big challenge not only because of the interface between diamond and AlN but also for the high roughness of the diamond surface [3, 4]. Nano and micro-crystalline diamond surface roughness were studied by AFM. We have deposited on three different NCD wafers and a polished MCD. The average surface roughness was analyzed at different spots within each wafer, and the average results were 10.7 nm, 6.7 nm and 5.8 nm RMS for the NCD wafers, and 3.7 nm RMS for the MCD. The differences between nano and micro-crystalline diamond surface roughness by AFM can be observed in Fig. 1.

We have studied the influence of the diamond surface roughness on the c-axis orientation of the AlN thin film. Fig. 2 shows how an increase in the discharge power influences the full width at half maximum (FWHM) of the rocking curve for AlN (002). It has been reported that an increase of discharge power produces a narrower FWHM [2]. In our case, the roughness of the diamond substrate also plays a role. For the smooth MCD, the behaviour is as expected. However, the high surface roughness of the NCD entails a different behaviour regarding the discharge power. Even for the smoothest NCD, in which we observe a decrease in the FWHM of the 002-rocking curve increasing power, there is a noticeable difference between less rough NCD and the smooth MCD substrate.

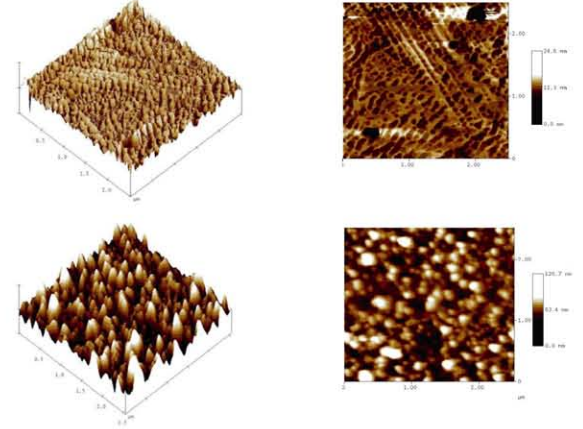


Figure 1. 3D and height AFM micrographs of microcrystalline diamond (roughness of 1.9 nm RMS, 2.5 μ m scan size and data scale of 17.8 nm for the 3D image), on top, and nanocrystalline diamond (roughness of 10.8 nm RMS, scan size of 2.5 μ m and data scale of 49.5 for the 3D image), at the bottom.

The influence of the AlN thickness on the FWHM 002-rocking curve has also been studied. AlN films from approximately 150 nm until 3 μ m were deposited on the MCD substrate. As shown in Fig. 3, the crystal quality improves for thicker AlN layers, and the FWHM of the 002-rocking narrows down to 2° for layers thicker than 1 μ m.

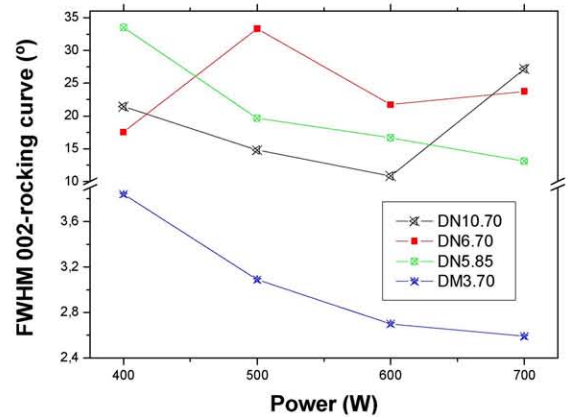


Figure 2. FWHM of the 002-rocking curve for different substrate surface roughness.

Fig. 4 shows the columnar growth of the AlN on the diamond substrate observed by TEM with two regions of the AlN layer grown directly on the diamond substrate recorded in BF conditions. The respective insets correspond to the electron diffraction of the regions indicated by the dashed circles. This is achieved using the selective area aperture and micrographs are recorded with and without it.

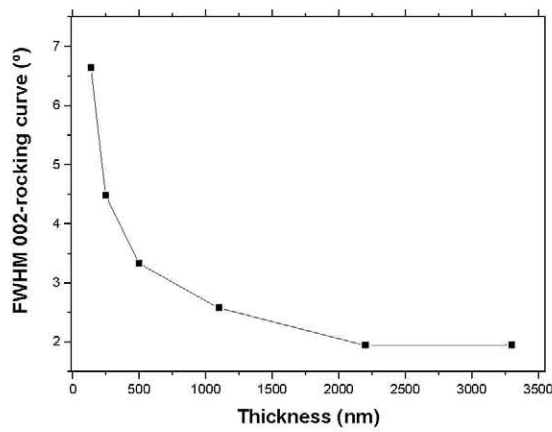


Figure 3. Influence of the AlN layer thickness on the FWHM 002-rocking curve.

In Figures 4a, 4b the aperture is located at the bottom and the top of the AlN layer, respectively. The corresponding SAED patterns show that the spots change from circular shape to a well defined spot. This indicates that the grain disorientation is reduced with the layer thickness. Near the interface the grains have an estimated disorientation of around 20° while at the top of the layer grains are perfectly oriented.

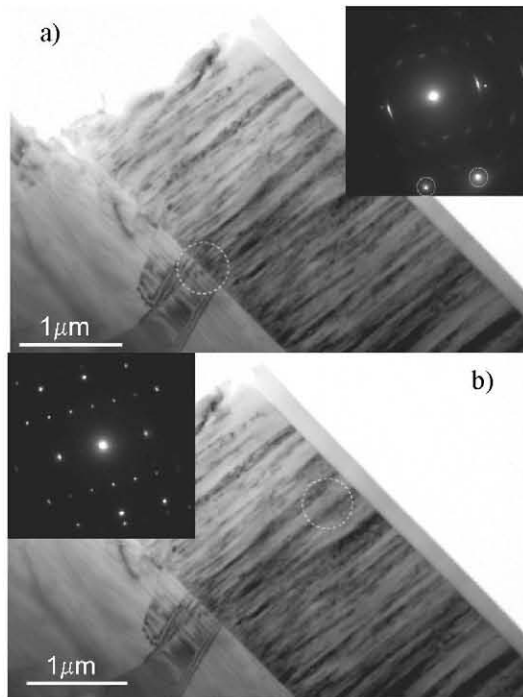


Figure 4: Micrographs of the AlN layer recorded in BF conditions. The insets correspond to the SAED recorded at the dashed circle locations, i.e. these circles correspond to the aperture location. The “circular” (elongated) spots result from the addition of small spots each one corresponding to a grain, so that this grain disorientation induces this “circular-like” aspect.

This interpretation is corroborated by the DF observations of Fig. 5. The white grains near the diamond-AlN interface are grains slightly disoriented. They did not extend up to the layer surface and only the well oriented ones follows above 500 nm. The observed layer thickness is $1.85 \mu\text{m}$ and, thus, the AlN layer surface is reached only by columnar grains.

The layers have been used to fabricate one-port SAW devices. The frequency response obtained for one of them is shown in Fig. 6. The structure is a $3 \mu\text{m}$ thick AlN layer deposited on $8 \mu\text{m}$ of microcrystalline diamond, with a rocking curve FWHM of 2.5° . The IDT consists of 400 fingers with $\lambda = 10 \mu\text{m}$. The central frequency of 620 MHz corresponds to a v_p around 6200 m/s, higher than the sound velocity for the AlN due to wave propagation through the substrate.

More work is underway in order to reduce the IDT size and optimize the AlN/diamond heterostructure.

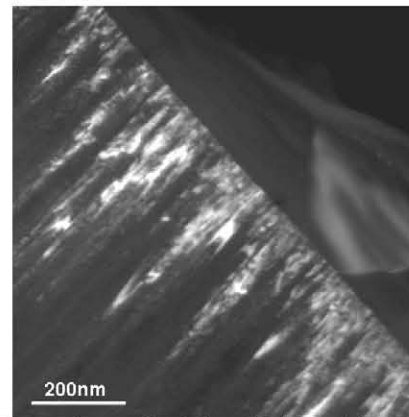


Figure 5: DF micrograph of the AlN-diamond interface. Columnar grains are observed and the white contrasts correspond to grains out of the layer orientation.

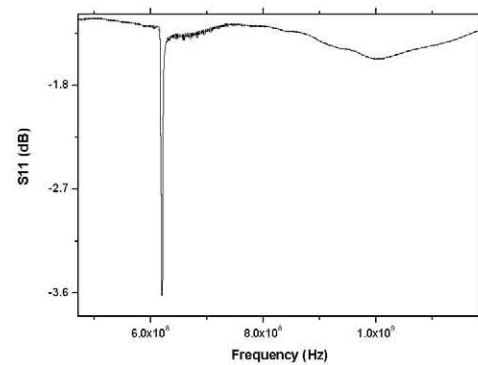


Figure 6. S11 parameter of a one-port SAW resonator processed on AlN/diamond.

IV. CONCLUSIONS

AlN/diamond is a promising structure for high frequency SAW devices. The influence of the surface roughness of NCD and MCD on the crystal quality of sputtered AlN thin films has been studied. The best crystal quality AlN thin films were obtained for the smoother diamond. SAW resonators were processed using these structures with very promising performances.

ACKNOWLEDGMENT

This work has been supported by Ministerio de Ciencia e Innovación, under the MINANI (TEC2007-67065/MIC) and ReADi (TEC2010-19511) projects, and the Acción Integrada DE2009-0015.

REFERENCES

- [1] G.F. Iriarte, "Surface acoustic wave propagation characteristics of aluminum nitride thin films grown on polycrystalline diamond", *Journal of Applied Physics*, vol. 93, No. 12, 15 June 2003.
- [2] G.F. Iriarte, J.G. Rodríguez, and F. Calle, *Materials Research Bulletin*, "Synthesis of c-axis oriented AlN thin films on different substrates: A review" vol. 45 pag. 1039- 1045, September 2010.
- [3] Cheng-Hsien Chou, Yung-Chen Lin, Jin-Hua Huang, Nyan Hwa Tai and I-Nan Lin, "Growth of high quality AlN thin films on diamond using TiN/Ti buffer layer", *Diamond and Related Materials* 15, pp. 404-409, 2006.
- [4] O. Elmazria, F. Bénédict, M. El Hakiki, H. Moubchir, M.B. Assouar, F. Silva, "Nanocrystalline diamond films for surface acoustic wave devices", *Diamond and Related Materials* 15, pp. 193-198, 2006.